On the Problem of Measuring Interannual Wind Speed Variations Using SSMI Data

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ABSTRACT

The first Special Sensor Microwave Imager (SSMI) was launched on the Defence Meteorological Satellite Program (DMSP) F8 spacecraft in July 1987, and wind speed was no longer retrieved after December 1991. A second SSMI was launched on DMSP F1O in December 1990. Interpretation of the 1987-1993 (or longer) SSMI wind speed time series is dependent upon the space and time characteristics of the differences between F8 and F1 O SSMI measurements. The 10°-zonal averaged month] y mean F8-F1 O wind speed difference was negative (positive) for wind speeds less (greater) than 7.9 m s^{-1}, reaching -0.43 (0,32) m s^{-1} at 5 (10) ms^{-1}. Between 60°S and 60°N the 10°-zonal averaged monthly mean F8-F1 O wind speed bias was greater than ± 0.5 m s^{-1} on several occasions. From 60°S - 60°N the 1991 average value of the monthly mean root-mean-square difference between daily F8 and F1 O wind speeds in 10°-longitudinal bands was 2.0 m s^{-1}. In the 60°S - 60°N region, about 50% of the daily F8 and F1O wind speed differences was caused by measurement non-simultaneity and about 50% of the difference was attributed to other factors, such as instrument noise and the different locations of the SSMI on the spacecraft. Caution is advised in the interpretation of large-scale monthly mean analyses obtained from a combined F8 and F1 O wind speed time series.

1. Introduction

Studies of seasonal-to-interannual global air-sea fluxes of heat and gases, including carbon dioxide and water, require multi-year time series of surface wind speed at time and space resolutions of about one month and one- to two-hundred kilometers, To compute a monthly mean surface wind speed, frequent measurements are needed to describe submonthly variations. Wind speeds need to be measured at relatively close spacing to resolve the natural spatial variability produced by ocean-atmosphere phenomena such as the western boundary current, equatorial upwelling, and the Intertropical Convergence Zone (ITCZ).

For more than a century the large-scale distribution of wind speed has been measured from ships and the sampling distribution of ship observations was, and continues to be, very uneven, with immense regions of the southern hemisphere ocean not measured for many successive months. For the past two decades, estimates of the surface wind field over the global ocean have been routinely generated in operational numerical weather prediction centers which, however, continuously change the forecast-analysis system. Recently, measurements from satellite-borne instrumentation yield uniformly-processed estimates of the global surface wind field during the approximate 3- to 5-year lifetime of the instrumentation.

With the launch of the Special Sensor Microwave Imager (SSMI) in July 1987 on the United States Air Force Defence Meteorological Satellite Program (DMSP) spacecraft F8, the global surface wind speed distribution was measured approximately every 3 days. Additional DMSP spacecraft equipped with an SSMI have been launched in December 1990 (F1O spacecraft) and in November 1991 (F11 spacecraft) and more instruments are scheduled for launch during the next decade which, if successful, will produce a 10- to 15-year time series. Because the F8 SSMI wind speeds were no longer retrieved after December 1991, interpretation of a composite time series of SSMI wind speeds from 1987 to the present time requires evaluation of the differences between SSMI data recorded on both F8 and F1O spacecraft during the 1-year overlap (January - December 1991). The question, what is the space-time structure of the F8 and F1O SSMI wind speed difference?, is addressed in this paper, emphasizing large geographical regions and 1-month time scale.

The SSMI is a 7-channel, 4-frequency, linearly polarized, passive microwave radiometer. The intensity of microwave radiation emitted at the ocean surface is affected by sea surface roughness, which is correlated with surface wind speed. Remote Sensing Systems of Santa Rosa, California, used the Wentz [1989, 1992] procedure to process 37-GHz vertically- and horizontally-polarized brightness temperature observations into 10-m height wind speeds. The data processing procedure remained unchanged for F8 and F1O SSMI measurements. The model function relating wind speed to electromagnetic radiance was considered invalid within 100 km of land and 200 km of sea ice edge, and when the total liquid water content in the atmosphere was greater than 0.25 kg m^{-2} because in each case there would be a marked change in radiative scattering.

In addition to uncertainties underlying the relationship between emissivity of the sea surface and wind speed, including the attenuation of the electromagnetic radiation by the atmosphere separating the spacecraft and sea surface, the spacecraft orbit influences the measurement of brightness temperature. The average F8 and F1O altitudes were different, the F8 swath width was almost constant at 1395 km in contrast to the 1225- to 1427-km swath width of F1 O, and the F8 and F1 O measurement incident angles were not the same. Measured brightness temperature is related to incidence angle. The F8 and F1O incidence angle difference was typically 0,2°, which corresponds to a brightness temperature difference of 0.2 K for horizontal polarization and 0.4 K for vertical polarization. The F1 O brightness temperatures were adjusted by the Remote Sensing Systems during the data processing so that the F8 and F1 O wind speed measurements were independent of the different incident angles.

The accuracy of the F8 SSMI wind speeds was determined by comparison with moored-buoy wind measurements at about 50 sites in the Atlantic and Pacific Oceans during 1991 [see Halpern, 1993, for description of methodology]. The root-mean-square (rms) difference of 297 monthly mean SSMI and moored-buoy wind speed matchups during 1991 was 1.0 m s^{-1}, which was considerably less than the 3-4 m S^{-1} rms accuracy of wind measurements recorded by ships [Esbensen et *al.*, 1993]. The annual mean SSMI wind speed was 0.2 m s^{-1} less than that computed from the moored-buoy measurements, in marked contrast to the 1-2 m s^{-1} bias between ship and buoy data [Esbensen *et al., 1993].* The range of the moored-buoy monthly mean wind speeds was 2 to 11 m s^{-1}. The correlation coefficient between SSMI and buoy matchups was 0.81, which was significant at the 95% confidence level. The slope of the orthogonal regression line computed between monthly mean SSMI and moored-buoy wind speeds was 9% different than unity.

2. Results

The SSMI wind speeds occurred in non-overlapping areas of 25 km x 25 km, which were arrayed across the approximate 1300-km swath width. Geographical coordinates correspond to the center of each 25-km x 25-km region. The F8 and F1 O wind speeds located in non-overlapping 1/3° x 1/3° areas were each arithmetically averaged each day, Most 1/3° x 1/3° areas contained two or three SSMI wind measurements per day. The 1 /3° x 1/3° area was chosen to cm-respond to the horizontal grid of an ocean general circulation model used to simulate wind-driven upper-ocean currents in the tropical Pacific, and because it is the pixel size of a number of satellite-derived data products published in a series of atlases. A daily mean F8-F1O wind speed difference was computed for each 1/3° x 1/3° area containing collocated F8 and F1 O data.

Within each 102-min orbit, the F8 and F1O SSMI swaths overlapped on two occasions. Approximately 8.7×10^4 (standard deviation= 3.5×10^4) collocated F8 and F1O SSMI 1/3° x 1/3° wind speeds occurred each day throughout the year, except for January when the average number of daily matchups was 3.2x1 (F. The number of days during 1991 when F8 and F1O matchups occurred was 305. Two intervals when no F8 and F 10 matchups occurred were 1-11 February and 27 March -17 April. The representativeness of results associated with January, February and April would be less than that for other months.

a. Annual Mean Difference

The correlation coefficient between time series of 305 daily area-weighted F8 and F1 O wind speeds averaged over 60°S - 60”N was 0.7, which was not considered large because only 50% of the F8 and F1O annual variances were linearly related. The absolute value of the area-weighted 60°S - 60”N mean value (F8-F1 O = -0.07 m s^{-1}) was greater than one of three absolute values of year-to-year differences (0.04 m s^{-1}) of area-weighted annual mean F8 wind speeds during 1988-1991 and smaller than two F8-derived year-to-year differences (0.09 and 0.17 m s^{-1}). Thus, the 305-day mean bias between F8 and F1 O wind speeds over 60°S - 60”N was comparable to that corresponding to the interannual variability of the F8 SSMI wind speed during 1988-1991.

b. Monthly Mean Difference

The 60°S - 60°N arithmetic mean of the 10°-zonal averaged monthly mean F8-F1O bias, which had considerable variations throughout the year and over the 60°S - 60°N region (Figure 1A), was -0.12 m s^{-1}. The largest temporal variation of the F8-F1O wind speed difference occurred in the 50"N - 60°N band where the February to April variation was 1.4 m S^{-1}, which may not be representative because of limited data coverage in February and April. Between 60°S and 60"N the 10°-zonal averaged monthly mean F8-F1O wind speed bias was larger than 0.5 m S-l. A monthly mean wind speed uncertainty of 0.5 m s^{-1} could produce a net surface heat flux error of about 12 W m^{-2} [Ramage, 1984], which is the accuracy needed for studies of seasonal-to-interannual climate variations.

Throughout most of the year and over nearly the entire 60°S - 60°N region, F8 wind speeds were smaller than that of F1 O (Figure 1 B). The F8 wind speeds were larger than F 10 speeds in two regions, 60°S - 40°S and 30"N - 60°N. A secondary minimum (-0.2 m S-l) of the F8-F1O wind speed difference was associated with the ITCZ at about 5"N (Figure 1 B). The months and latitudes that the F8 wind speed was greater than F1O (Figure 1A) correspond to times and regions associated with wind speeds higher than the annual mean wind speed. Monthly mean F8 SSMI wind speeds during 1991 are displayed by Halpern *et al.* [1993].

A statistical correspondence existed between F8-F1 O wind speed differences and wind speed. The orthogonal regression line slope (O. 15) between 1-month 10°-zonal averaged F8-F1O differences (Figure 1A) and 1-month 10°-zonal averaged F8 wind speed (not shown) was significantly different than zero, according to the method described by Bendat and Piersol [1986]. The 95% significance level is used throughout the paper. Least-squares predictions of F8-F1 O wind speed differences would be -0,43, 0.0, and 0.32 m S^{-1} for F8 wind speeds of 5.0, 7.9, and 10.0 m S-l, respectively. The correlation coefficient (0.66) between the F8-F1O difference and F8 wind speed was significant. Thus, over the 60°S - 60"N region during 1991, F8 wind speeds were typically less (greater) than the F1O wind speed for speeds smaller (greater) than about 7.9 m S-l.

c. *RMS Difference*

The monthly mean 10°-zonal average rtns difference computed between daily F8 and F1O wind speed matchups increased from 1.5 m s^{-1} in the 20°S to 20°N tropical region to 2.5 m S-l at 50° latitude (Figure 2), During 1991 the 60°S - 60°N average rms difference (computed from the squared values displayed in Figure 2A) was 2.1 m S-l, which was fifteen times greater than the 60°S - 60°N annual mean bias. In middle latitudes therms differences seemed to correlate with the hemispheric winter season. In the Northern Hemisphere, rrns differences greater than 2.5 m S-l, which is the annual mean value at 45°N (Figure 2B), occurred from October to March. In the Southern Hemisphere, rms differences greater than 2.7 m S-l, which is the annual mean value at 45°S (Figure 2B), occurred from June to November. No evidence of an annual cycle of the rms difference was noted in the tropics.

The annual mean north-south distribution of therms difference between F8 and F1O wind speeds (Figure 2B) is very similar to that of the wind speed and standard deviation of daily wind speed, which have been described by Halpern et *al. [1994]*. These correspondences indicate an association between F8 and F1 O rms differences and the natural wind variability. The monthl y mean 10°-zonal rms differences (Figure 2A) and monthly mean10°-zonal F8 wind speed (not shown) were significant y correlated (correlation coefficient = 0.90) and the least-squares orthogonal regression line slope (0.25) was significantly different than zero. The rms differences increased with increasing wind speed. At 6, 8, and 10 m s^{-1}, the predicted month] y mean rms differences between daily F8 and F1O wind speeds are 1.7,2.2, and 2.7 m S-l, respectively.

3. **Instrument, Sampling, and Satellite Errors**

Sensitivities of the 37-GHz horizontal- and vertical-polarized radiometers on F8 were each about 0.4 K [Hollinger *et al.*, 1990], which is approximate y equivalent to an error of 1 m S-l. We assume that the sensitivity of the SSMI on F 10 was the same. Thus, the measurement resolution standard error of each F8 and F1 O collocation was about 1 m s-'. The monthly mean random error caused by imperfections in the instrument would be less than 0.13 m s^{-1} because more than 60 measurements were recorded each month in a 1/3° x 1/3° area.

It is hypothesized that the determination of SSMI wind speed is also dependent on the location of the instrument on the spacecraft, because the measured emissivity is related to the direction of the surface wind [Wentz, 1992]. The SSMI on F8 (F1O) was mounted on the back (front) of the spacecraft, At high latitudes, where the retrograde-orbit (satellite moves from east to west) groundtrack is aligned primarily along the east-west direction and where the wind direction is eastward, the SSMI on F8 (F I O) measured wind speed in the downwind (upwind) direction. For wind speeds greater than 7 m S-^{1}, Wentz [1992] reported that SSMI wind speeds were 2 m S-^{1} greater than and 1 m s^{-1} less than moored-buoy wind speeds (assumed to be representative of the true wind speed) for downwind and upwind directions, respectively, of the surface wind. The conjecture that the SSMI positions on the F8 and F1 O spacecraft influenced the measurements differently is consistent with the observations. For wind speeds greater than 8 m S-^{1}, which typically occurred for several winter-time months at high latitudes where the groundtrack was aligned primarily in an east-west direction, the F8 wind speeds were higher than that of F1 O (Figure 1) because the F8 SSMI 'looked' towards the direction of the surface wind (i. e., downwind) and the F1O SSMI 'looked' into the wind (i. e., upwind).

The non-simultaneity of the F8 and F1O wind speed measurements introduced an error in the comparison of collocated daily mean 1/3° x 1/3° F8 and F1 O wind speeds, which was evaluated on 1 November (an arbitrarily-chosen date during the month with the greatest number of matchups). Between 60°S and 60°N the average time and distance separating individual F8 and F1O wind speeds that occurred within 6 h and 25 km of each other were 2.0 h and 11.8 km. On 1 November there were about 2x 10^5 F8 and F1 O values that occurred within 6 h and 25 km of each other; these data are named 6-h 25 km data, in contrast to the daily 1/3° x 1/3° data which constituted the basic data for the analyses throughout the paper, The mean difference of the 6 h 25 km matchups was less than 0.005 m S-^{1} and therms difference was 1.7 m S-l. For the l-day averaged 1/3° x 1/3° data (1 .2x10^5 matchups on 1 November), the mean difference was 0.13 m S-^{1} and the rrns difference was 2.2 m S-l. In the 60°S - 60°N area, the non-simultaneous sampling created daily-averaged errors of 0.1 m s^{-1} in the bias and 1.4 m s^{-1} in therms difference between F8 and F1O measurements. The sampling-related standard error of the monthly mean 60°S - 60°N bias would be about 0.02 m s-], which is considerably smaller than the values in Figures 1. Analysis of the 100-average latitudinal distributions of the differences between the daily 1,3° x 1/3° and 6 h 25 km data sets for 1 November (not shown) revealed that the largest differences occurred poleward of 35°S where differences reached 0.4 m s^{-1} for the bias and 2.0 m s^{-1} for therms difference. These values were considerably larger than the corresponding differences bet ween 35°N and 60°N where the bias was approximately zero and the rms difference was 1.0 m s-l. In the 20°S - 20°N tropical zone, the differences between the daily 1/3° x 1 /3° and 6 h 25 km data sets were 0.1 m s^{-1} for the bias and 0.5 m s^{-1} for therms difference.

4. Conclusion

Studies of global seasonal-to-interannual oeean-atmosphere interactions require long time series of surface wind speed over the ocean, which, before the advent of earth-orbiting satellite-borne instrumentation, was not obtainable from in-situ methods because of the scarcity of observations over a large segment of the global ocean nor from numerical weather prediction centers because of continuous changes of the forecast-analysis schemes. Development of decade-long time series of global surface wind measurements for studies of seasonal-to-interannual climate variability presents unique challenges for space-borne instrumentation because of the necessity to combine data sets of 3- to 5-year lifetimes. Two SSM I wind data sets recorded during 1991 are examined. The Remote Sensing Systems processed S SMI radiance measurements into wind speeds using identical algorithm and model function for F8 and F1 O data,

Statistical evaluations of the 1/3° x 1/3° F8 and F10 matchups revealed the following: (i) 305-day mean area-weighted F8 wind speed between 60°S and 60°N was 0,07 m s^{-1} less than that of F1 O, and the difference was significant; (ii) poleward (equatorWard) of 40° latitude the F8 wind speed was greater (less) than that of F1 O (Figure 1 B); (iii) 305-day mean rms difference was 2.0 m s^{-1}, with larger values at middle latitudes during winter-hemisphere months and lower values throughout the year in the tropics (Figure 2B); (iv) regions with ambient wind speed greater (less) than 7.9 m s^{-1} were associated with monthly mean F8 wind speeds greater (less) than that of F1O.

In the 60°S - 60°N region, about 50% of the daily F8 and F1 O wind speed differences was caused by measurement non-simultaneity and about 50% of the difference was attributed to other factors, such as instrument noise and the different locations of the SSMI on the spacecraft. A new algorithm is being developed that uses the 19-GHz vertical polarized radiances with the 37-GHz horizontal and vertical polarized radiances to mitigate the wind speed error caused by the direction of the surface wind relative to the angle along which the radiation is measured.

In conclusion, differences between monthly mean F8 and F1 O wind speeds are large enough for caution to be advised in the interpretation of results produced from a combined F8 and F1O wind speed time series. For example, the absolute value of the area-weighted mean F8 and F1 O difference during 1991 was approximately the same as the year-to-year variations during the 1988-1991 period, This limits usage of a F8 and F1O composite 1987-1993 (and longer) SSMI wind speed data set to examine interannual variations of wind-speed dependent ocean-atmosphere interactions. The Remote Sensing Systems intends to modify its SSMI wind speed retrieval algorithm to remove the influence of surface wind direction, and to reprocess the F8 and F1O SSMI radiance measurements into wind speeds that will be more useful for studies of interannual wind speed variability.

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List of Figures

Figure 1. (A) Time-latitude section of 10°-zonal average monthly mean F8-F1 O wind speed difference or bias (m S-l), which were computed from F8 and F1O collocated daily 1/3° x 1/3° wind speeds. (B) North-south distribution of annual mean F8-F1 O wind speed bias.

Figure 2, (A) Time-latitude section of10°-zonal average monthly mean root-mean-square(rms) difference (m s^{-1}) between daily collocated 1/3° x 1/3° F8 and F1O wind speeds. (B) North-south distribution of annual mean rms difference between daily collocated 1/3° x 1/3° F8 and F1O wind speeds.

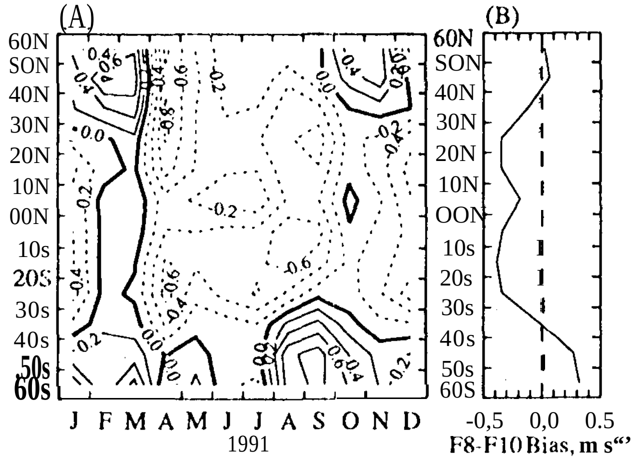

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Figure 1

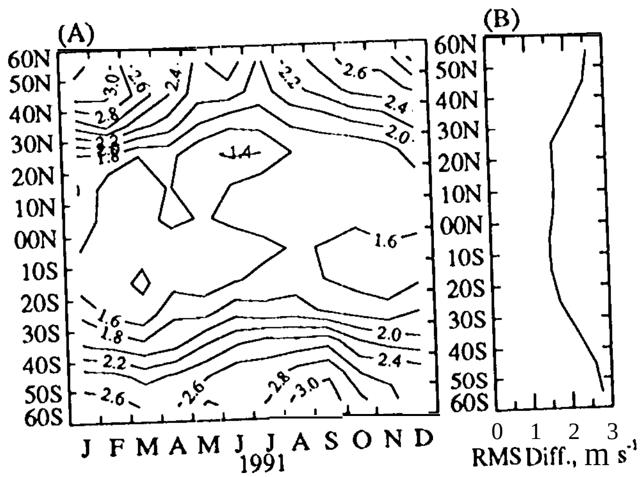
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Figure 2